Sizing of boilers for residential buildings

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SUMMARY

The tendency towards better insulated and energy friendly ventilated buildings leads to an ever decreasing building heat load. On the other hand, the installed boiler size is not altered. Often this is due to requirements of the coupled domestic hot water production, or worse, due to the superstitious belief that larger means better.
Correct sizing of the boiler can not only reduce the heating system investment cost, but also lower the energy consumption, and maybe even improve the thermal comfort. For this study, a simulation model has been set up in which the boiler's output capacity is varied and the resulting heating system evaluated for both thermal comfort and energy consumption. The simulations are performed for two natural gas boilers, i.e. a high efficiency and a modulating, condensing one. The performance of the boilers sized following the European standard design heat load calculation [1], is compared to the results of the broad range of thermal output capacities.
As expected, oversizing leads to increasing primary energy consumption, especially in the case of the High Efficiency boiler due to its inadequate control system and high skin losses. The heat load calculation from the European standard is not far from the optimum, but it overestimates the necessary reheating power after night set back.

INTRODUCTION

As the thermal resistance of a building enclosure increases, the impact of any additional thermal insulation on energy economy decreases. This physical law forces countries with tough insulation requirements to turn to Energy Performance Regulation (EPR). EPR not only evaluates thermal insulation, but also takes into account the energy efficiency of ventilation, lighting, hot water production and heating systems as well as the benefits of passive and active solar energy [2]. A great unknown in such a vast corpus of possibilities is the heating installation's efficiency. The efficiency should be determined on the building scale, so that interactions between heating system and building are included. By defining the overall efficiency as the ratio of the net heat demand of the building and the total energy consumption of the boiler, control losses are included, but also the partly recovering of distribution and boiler losses can be assessed.
Since the net heat demand is a theoretical consumption minimum, and can not be measured like the real energy consumption, TRNSYS 16.1 is used to simulate different types of boilers, different boiler controls as well as different emission controls in houses with varying insulation quality [3]. It is shown that the boiler size has an important influence on the efficiency of the heating system.

The estimation of the required thermal power is not evident. Standard calculation methods have been developed. However, as Corrado [4] and Wouters [5] state, standardization, and as a consequence simplification, of the heat load calculation must be done carefully. In this paper the boiler size is assessed to maximize the heating system efficiency while maintaining the indoor thermal comfort. This result is then compared to the boiler size as determined by the European standard procedure [1].

METHODS

The building is a compact terraced house with an outer volume of 446 m³ and an exterior surface of 226 m². The heated ground floor (level 0) has an area of 63 m². The day zone, which comprises the kitchen, hall and living room, has a floor area of 50 m². Its set temperature during the day is 21°C, the implemented night set back allows a temperature decrease down to 15°C. The first floor (level 1) includes a hall (14.3 m²), two bed rooms (16.3 m² and 19.3 m²) and the bathroom (6.6 m²). This last zone has a set temperature of 24°C during the day and 21°C during the night. The bed rooms are not heated. The upper floor (level 2), partly under the sloped roof, comprises a study (14.1 m²), a storage room (4.8 m²), the third bedroom (21.5 m²) and the upper part of the hall (16 m²). The study and hall are both heated as the day zone, while the other rooms on this floor are not heated. The boiler, however, is located in the storage room and thus indirectly heats this volume.
The average U-value of the building envelope is 0.8 W/m²K, which leads to a net annual energy demand for space heating equal to 11 573 kWh. The heat emission system consists of low temperature radiators and thermostatic radiator valves (TRVs). The ventilation is modelled as non-forced natural ventilation as described in the Belgian standard NBN D50-001 [6].
The building as described above is modelled in TRNSYS 16.1. A detailed description is available in [7]. The low temperature radiators are modelled on Type 72 from IEA Annex 10 and numerically optimized by Kummert [8]. They are dimensioned according to the technical reports of the Belgian Building Research Institute [9]. Each radiator is equipped with TRVs. In the framework of IEA Annex 10, a simplified TRV-model has been developed by Ast [10]. It is a lumped capacitance model of the temperature sensor including the (relatively small) thermal resistance of the casing and the (larger) thermal resistance between sensor and water. Further refinements and measured data have allowed to develop a representative model of a programmable TRV in TRNSYS.
The boiler models for both the condensing and the high efficiency gas boiler are elaborate refinements of the TESS-boiler model ([11] and [12]). The input data is based on test data and a static boiler EES model developed by Lebrun [13]. The TRNSYS boiler models can be regarded as a combination of an ideal heater and a lumped capacitance model. The ideal heater, the burner, is immediately turned on or off as requested by the boiler control logic. The heated water then 'passes' the capacitive element. This part also models the heat losses through the boiler's envelope. The boiler's water exhaust temperature, leaving the capacitance, is thus lower than the burner's water outlet temperature.
The boiler's control logic can be set to an on/off regime or to a modulating regime so that the Part Load Ratio (PLR) can vary between 25% and 100%. The high efficiency boiler is modelled as a non-modulating system. It is turned on if the TRVs allow water flow. If the water exhaust temperature exceeds the maximum water outlet

temperature, the boiler is turned off again. Obviously, this working regime leads to frequent cycling. The condensing boiler can modulate to a quarter of its maximum thermal power. The latter is equipped with an external temperature compensated control. If the requested PLR becomes lower than 25%, this boiler will have to cycle as well.
The boiler is switched off during night set back. However, during day time, the boiler is required to maintain its operation temperature, since it is coupled to TRVs which can always demand heat.
The simulations are performed with varying boiler sizes. Firstly the thermal power as calculated based on the European standard is determined for four reheat time periods, i.e. the heating system is turned on one, two, three or four hours before the set temperature has to be reached. This leads to four surplus powers for intermittent heating (Table 1) and thus four boiler sizes as shown in Table 2. Secondly, a range of power levels from 3 kW to 30 kW is simulated. Auxiliary power, thermal capacity, as well as the thermal transmittance of the boiler envelope varies proportionally. The reheat time is set to one hour for this range.
The European standard EN 12831 [1] specifies a method for calculation of the design heat load of either a heated space or an entire building. The focus in this paper is on dwellings, heated with a central heating system. The European standard calculation for the total building design heat load ϕ_{HL} is[1]:

$$\phi_{HL} = \sum \phi_{T,i} + \sum \phi_{V,i} + \sum \phi_{RH,i} \quad (1)$$

where $\phi_{T,i}$ indicates the transmission heat losses of the heated spaces, excluding the heat transferred towards other zones inside the building, $\phi_{V,i}$ indicates the ventilation losses of the heated spaces excluding heat transferred in the building and $\phi_{RH,i}$ indicates the reheat capacities of the heated spaces required to compensate for the effects of intermittent heating.
The building is considered as a whole, therefore, internal heat transmissions are not taken into account. The EN 12831-standard aggregates the transmission losses through this building envelope to be 4.2 kW. The ventilation losses are calculated based on the volume flow rates for natural non-forced ventilation [6]. This results in a design heat loss for ventilation equal to 3.0 kW. For the surplus due to intermittent heating, a cold winter day is considered: the simulated temperature drop during night set back amounts to 3°C, averaged over the building zones. The thermal power to compensate for intermittent heating, as a function of the reheat time for a 3°C temperature drop is given in Table 1.

Table 1: Surplus in thermal power due to intermittent heating after a 3°C temperature drop

Reheat time (h)	1	2	3	4
Surplus for intermittent heating (kW)	3.8	1.9	1.4	1.1

Summing up the thermal loads due to transmission, ventilation and intermittent heating, results in the design heat load. To determine the necessary thermal power of the boiler, the emission and control efficiency have to be taken into account [14]. That means a division by a factor 0.97. A safety margin is applied to calculate the thermal

[1] The simplified calculation method can be used as the restriction on the air exchange flow rate, n_{50} being lower than $3h^{-1}$, is fulfilled.

power of the boiler, i.e. the power is multiplied by 1.1. Table 2 shows the resulting thermal power levels.

Table 2: Total thermal power as a function of reheat time, according to the European standard [6].

Reheat time (h)	1	2	3	4
Thermal power to install(kW)	12.6	10.4	9.8	9.5

The thermal comfort is determined based on an adapted weighted temperature excess method. This method is developed to assess overheating and is based on the Predicted Mean Vote (PMV)-model as developed by Fanger [15]. The aim of this paper, however, is to evaluate the thermal comfort for varying boiler sizes. Therefore only 'underheating' periods during the heating season will be included, i.e. when the indoor temperature does not reach the set value of the heated room during day time. The Weighted Temperature Subceeding hours (WTS) method is defined as follows:

$$PMV_i > -0.5 \rightarrow WF_i = 0 \qquad (2)$$

$$PMV_i \leq -0.5 \rightarrow WF_i = \frac{\sum PPD_i}{10.16} \qquad (3)$$

Where i indicates the zone and WF the hourly weighting factor. When the PMV is higher than -0.5, or put otherwise, when is predicted that less than 10% of the people judge the room too cold, the weighting factor equals zero. In the other case, when more than 10% thinks it is too cold, the factor is directly proportional to the Predicted Percentage of Dissatisfied (PPD). Finally, the WTS-hours are calculated as the sum of these hourly weighting factors during the whole heating period.

The energy consumption of the whole heating installation will be assessed. The circulation pump's working regime is determined by the boiler's working load; therefore, pump's energy consumption should be included. The energy input of the heating installation consists of natural gas (gas_{cons}) and electricity ($elec_{cons}$). As the energy consumption is expressed in primary energy (PE_{cons}), a conversion factor for electricity (f_{conv}=2.5 [16]) is used:

$$PE_{cons} = gas_{cons} + f_{conv} \cdot elec_{cons} \qquad (4)$$

The overall efficiency is then defined as the ratio of the net energy demand of the building and the total primary energy consumption. The boiler efficiency can be defined as the ratio of the useful boiler output, i.e. the increase of energy of the water flowing through the boiler, and its primary energy consumption. The Higher Heating Value (HHV) is used throughout this paper.

RESULTS

As this paper focuses on both the indoor thermal comfort and the energy consumption, Figure 1 and Figure 2 show these variables as function of the boiler output capacity for both the high efficiency and the condensing gas boilers. Figure 1 shows that the indoor climate is acceptable for a heat output of at least 8 kW. The indoor climate is not influenced by oversizing the boiler. The effect of oversizing, however, can be seen in the increased energy consumption (Figure 2) and is mainly due to decreasing boiler efficiencies (Figure3). The effect is much more pronounced for non-modulating high efficiency boilers with a fixed water outlet temperature.

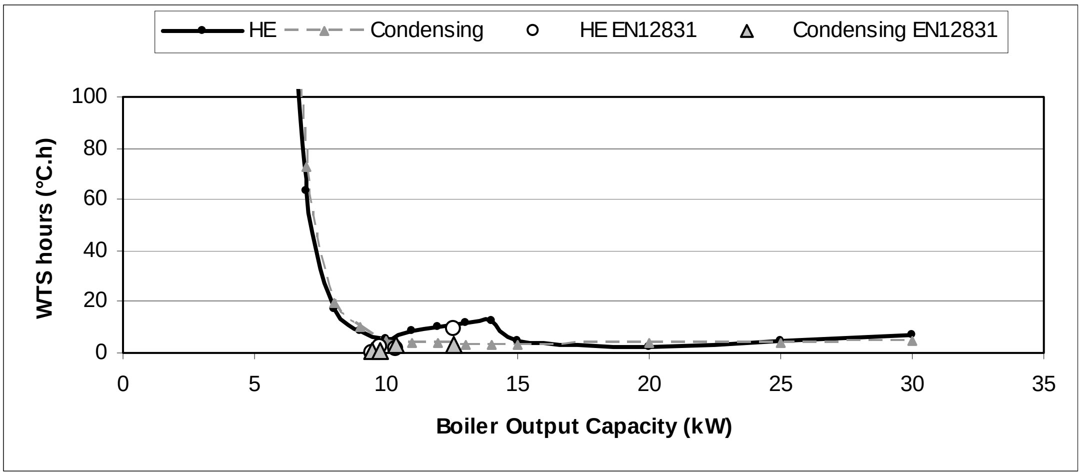

Figure 1: Weighted Temperature Subceeding hours versus the boiler output capacity for High Efficiency and Condensing boilers. The EN12831-cases are the boiler sizes determined by the European heat load calculation code with reheat times from one to four hours.

Figure 2 shows that the electricity use is low compared to the consumption of natural gas, so the effect on the primary energy use is limited. The higher electricity consumption for lower thermal power is due to increasing working time. For increasing boiler size, the cycling frequency increases (as shown in Figure 4), the number of working hours decreases and thus the auxiliary electricity consumption lowers as well. This effect counterbalances the growing ventilator power due to increasing boiler size. The modulating boiler can additionally profit from lower part load ratios and thus lower ventilator consumptions.

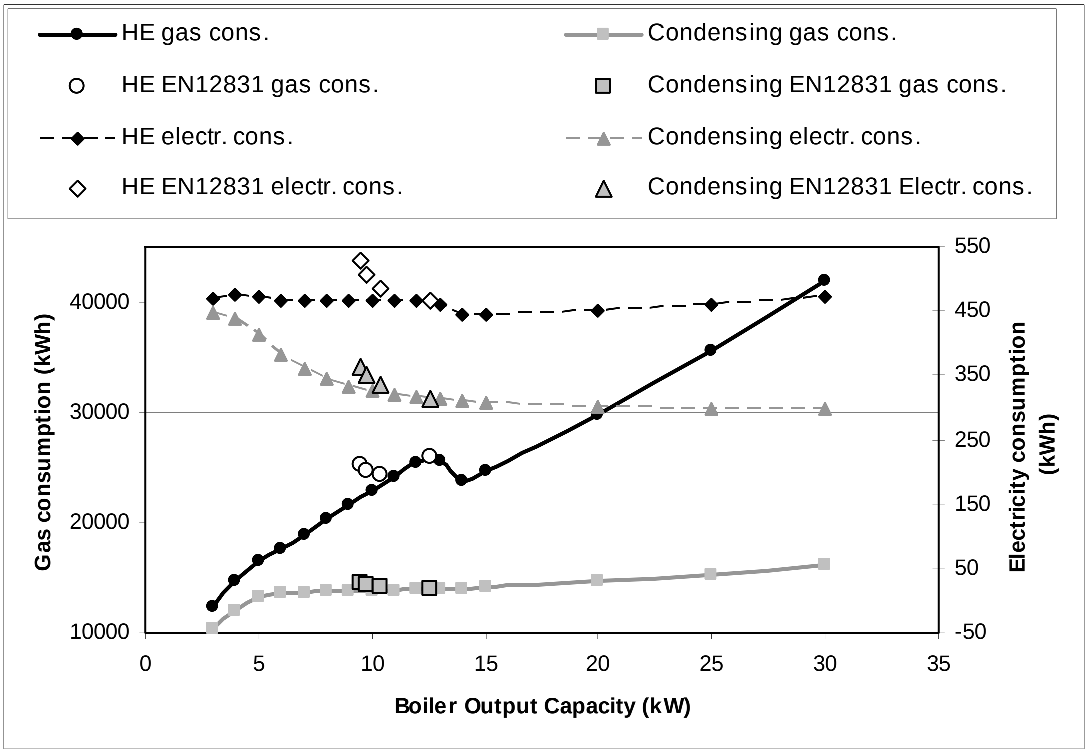

Figure 2: Gas and electricity consumption versus the boiler output capacity for both the High Efficiency on/off boiler and the Condensing modulating boiler.

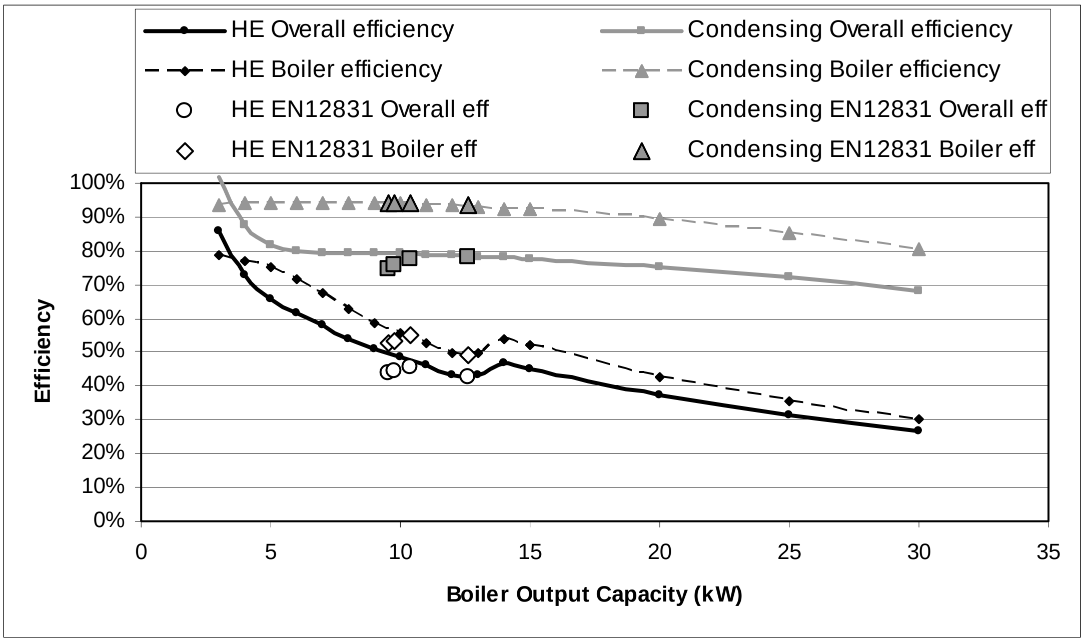

Figure 3: Overall efficiency (net heat demand / primary energy consumption) and boiler efficiency (net boiler output / primary boiler consumption at HHV) versus the boiler output capacity for both boiler types.

The decreasing boiler efficiency is correlated to the increasing cycling frequency. For boiler sizes under 6 kW, the cycling is limited. As Figure 4 shows, the boiler temperature stays below expectations despite almost continuously being switched on. The energy consumption and overall efficiency for these very low boiler output capacities are however not meaningful, since the boundary condition, a minimal indoor comfort, is not reached. The net heat demand is even bigger than the energy consumption in the case of a 3kW boiler. Therefore results below 8 kW should be neglected as a solution, but they are still visualised to show the trends.

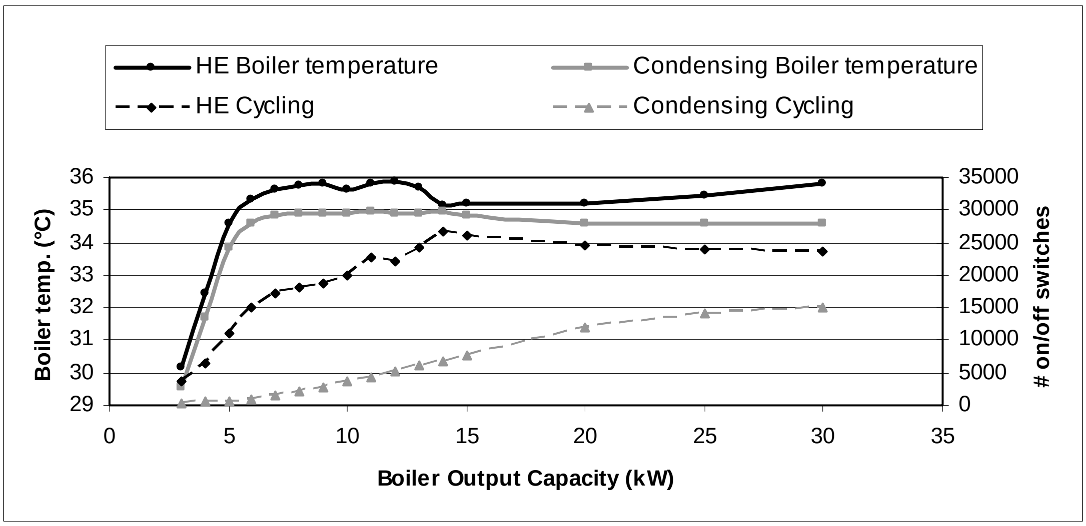

Figure 4: Boiler temperature and number of on/off switches versus the boiler output capacity for both boiler types.

Increasing the boiler size leads to more satisfying indoor conditions and a stable boiler temperature, but also implies a higher cycling frequency. The tendency of this

curve, though, changes for the different boiler types when further increasing the power. The high efficiency boiler, which is a non-modulating system, shows a maximum cycle frequency for thermal sizes slightly above the required heating power, around 15 kW. Modulating, condensing boilers with variable outlet temperature will smoothly tend towards the curve for non modulating systems, as extreme oversizing leads to a comparable working regime.
The results for the four boiler sizes as determined based on the European standard [1] diverge at the lowest boiler output capacities. This is due to the corresponding reheat times of one to four hours, while for the simulations of the range of boiler sizes one hour reheat time is used in all cases. The simulations show that this short reheat time is large enough during most of the heating season, except for a short period in winter. As a result, the increase in night set back time implies only a slightly better thermal comfort (Figure 1), but mainly a higher gas and electricity consumption (Figure 2). A temporary increase of the reheat time, or even adapted winter clothing could offer the same comfort but at a much lower energy consumption.
Deviant behaviour for boiler sizes of around 15 kW can be observed: lower thermal comfort (Figure 1), lower average boiler temperatures (Figure 4) and higher boiler efficiency (Figure 3). The main reason is that the oversizing results in frequent cycling, easily reached maximum temperatures and thus average boiler temperatures that are rather low (Figure 4). This effect is more pronounced during spring and fall. Lower temperatures allow more fume gas heat to be recovered and thus higher boiler efficiency, as can be seen in Figure 3. The modulating capacities cause much smoother curves for the condensing boiler.
Considering both thermal comfort and primary energy consumption, a thermal power from 9 kW to 11 kW leads to the best option, given the boundary conditions, i.e. in the case of the considered terraced house equipped with the specific heating system.

DISCUSSION

Oversizing does not influence the indoor thermal comfort, but leads to increase of primary energy consumption. However, there is a pronounced difference between boiler types. The condensing boiler can maintain its high efficiency quite well, due to low envelope losses, the ability to modulate its power down to 25%, and an outdoor temperature compensated boiler temperature which reduces the boiler temperature and thus skin losses even more.
The High Efficiency boiler with its simple on-off control, at the other hand, shows increasing difficulties to offer a constant water temperature to the TRVs with increasing boiler size. The boiler is required to cycle more and more, which leads to higher boiler temperatures and thus higher boiler losses. This is combined with a constant useful heat output and thus fast decreasing boiler efficiency. For these boilers a central room thermostat would offer a better solution, since this control allows the boiler to cool down between short intervals of (larger) heat demand.
The building heat loads calculated following the European standard only slightly overestimate the boiler size. However, the additional thermal power for intermittent heating seems difficult to predict. The corresponding reheat time is often overestimated, decreasing the overall efficiency. To put it otherwise, the heat load calculated for a reheat time of 4 hours suffices to heat up the building in slightly more than one hour.

REFERENCES

1 EN 12831:2003. Heating systems in buildings-Method for calculation of the design heat load. CEN, European Committee for Standardization, Brussels, Belgium.
2 Hens, H and Verbeeck, G, 2001. Heating efficiency, the great unknown. Clima 2001 proceedings, Napoli, Italy.
3 Peeters, L, Helsen, L and D'haeseleer W. 2007. Optimisation of extremely low energy residential buildings, final report: Advanced control strategies. K.U.Leuven, Belgium.
4 Corrado, V. 2003. About simplification assumptions for the evaluation of building thermal performance. Proceedings of the 2nd international conference on building physics, pp 657-664, Antwerp, Belgium.
5 Wouters, P, Van Orschoven, D, Vandaele, L and Schietecat, J. 2003. The scientific and technological challenges of buildings regulations in relation to a correct performance assessment of the energy performance and indoor climate in buildings. Proceedings of the 2nd international conference on building physics, pp 665-670, Antwerp, Belgium.
6 NBN D 50-001:1992. Ventilation facilities in residential buildings. Belgian National Institute for Standardization, Brussels, Belgium. (in Dutch)
7 Verbeeck, G and Hens, H. 2006. Optimisation of extremely low energy residential buildings, final report : part 2. K.U.Leuven, Belgium. (in Dutch)
8 Kummert, M. 2001. Contribution to the application of modern control techniques to solar buildings. Simulation-based approach and experimental validation. PhD thesis. FUL, Arlon, Belgium.
9 De Meulenaer, V and Van der Veken, J. 2004. Optimisation of extremely low energy residential buildings, final report : heating system simulation. K.U.Leuven, Belgium. (in Dutch)
10 Ast, H. 1988. Annex 10 System simulation, Thermostatic Valve. University of Stuttgart, IEA, Paris, France.
11 Van der Veken, J, De Meulenaer, V and Hens, H. 2006. Optimisation of extremely low energy residential buildings, final report : heating system. K.U.Leuven, Belgium. (in Dutch)
12 Thornton, J, Bradley, D and McDowell, T. 2004. TESS Component Libraries v 2.0 for TRNSYS 16 and the TRNSYS Simulation Studio, Thermal Energy System Specialists, LLC, Madison, Wisconsin, USA.
13 Lebrun, J., personal communication with Thermodynamics Laboratory. ULg, Liège, Belgium.
14 prEN 14335:2002. Heating systems in buildings, methods for calculation of system energy requirements and system efficiencies. CEN, European Committee for Standardization, Brussels, Belgium.
15 Fanger, P O. 1972. Thermal Comfort. Mc Graw-Hill, New York, USA.
16 EURELECTRIC, 2005. Statistics and prospects for the European electricity sector (EURPROG 2005). Brussels, Belgium.